

Quantum Information Processing using coherent states in cavity QED

Ming Yang^{1,*} and Zhuo-Liang Cao^{1,†}

¹*School of Physics & Material Science, Anhui University, Hefei, 230039, PRC*

Using the highly detuned interaction between three-level Λ -type atoms and coherent optical fields, we can realize the C-NOT gates from atoms to atoms, optical fields to optical fields, atoms to optical fields and optical fields to atoms. Based on the realization of the C-NOT gates we propose an entanglement purification scheme to purify a mixed entangled states of coherent optical fields. The simplicity of the current scheme makes it possible that it will be implemented in experiment in the near future.

PACS numbers: 03.67.Hk, 03.67.Mn, 03.67.Pp

Entanglement plays a key role not only in refuting the local "hidden variable" theory [1, 2] but in quantum information processing also, such as quantum teleportation [3, 4], quantum dense coding [5, 6], quantum cryptography [7, 8] and so on.

The preparation of entangled states becomes a vital step in quantum information processing (QIP). Recently, the generation of entanglement has been realized by NMR [10, 11], SPDC [9, 12], Cavity QED [13, 14], and Ion Trap [15] schemes. The generation scheme for polarization entangled photon state using SPDC has been reported [9], and it has been realized in experiment. Now, the techniques for generating entangled photon pairs have become rather mature. At the same time, quantum teleportation of unknown photon state and quantum cryptography process are all realized in experiment [4]. But, for the entangled atomic state, it is not the case. Although many theoretical schemes for the generation of entangled atomic state have been proposed, the number of the schemes that can really be realized in experiment is very small. Hitherto, only the entanglement of two atoms has been realized experimentally [14, 16]. The teleportation and cryptography schemes can not yet been implemented in experiment for atoms. To realize the atom-based quantum information processing, we must present more experimentally efficient atom-base QIP schemes.

In view of the previous QIP schemes, we found that the quantum controlled-not (C-NOT) gate is the key part of a total scheme. C-NOT gate can not only generate entangled states but realize the teleportation process through Bell state measurement also. In the cavity QED domain, the schemes for C-NOT gate have been proposed. By far the most efficient scheme is the one proposed by Zheng [14], where the interaction between two atoms induced by a dispersive cavity mode plays a key role and the C-NOT operation from atom to atom has been realized.

In this contribution, we will propose an efficient scheme to realize the C-NOT gates between atom and field of coherent light. The C-NOT operations involve four kinds:

C-NOT gate from atom to field of coherent light, C-NOT gate from coherent light to atom, C-NOT gate from one atom to another and C-NOT gate from one field to another. Being more efficient than the proposal of Zheng [14], our scheme not only can generate multi-atom entangled states but also can generate multi-mode entangled coherent states. The scheme is mainly based on the dispersive interaction between atoms and coherent optical fields.

Consider the interaction between an Λ -type three-level atom and a coherent optical field. Here the two lower levels of the atom are degenerate, and the frequency of the coherent optical field ω_c is largely detuned from the atomic transition frequency ω_0 between the degenerate lower levels and the upper level. In this large detuning limit, the upper level $|i\rangle$ can be adiabatically eliminated during the interaction.

Then the effective Hamiltonian for the system can be expressed as follow [17]:

$$\hat{H} = -\lambda a^\dagger a(|e\rangle\langle g| + |g\rangle\langle e|) - a^\dagger a(\beta_1 |e\rangle\langle e| + \beta_2 |g\rangle\langle g|) \quad (1)$$

where $\lambda = g_1 g_2 / \Delta$, $\beta_1 = g_1^2 / \Delta$, $\beta_2 = g_2^2 / \Delta$, with $\Delta = \omega_0 - \omega_c$ being the detuning between atomic transition frequency and the frequency of the coherent light, g_1, g_2 being the coupling constant between the cavity mode and the transitions $|i\rangle \rightarrow |e\rangle, |i\rangle \rightarrow |g\rangle$ respectively. Suppose $g = g_1 = g_2$, $\lambda = \beta_1 = \beta_2 = g^2 / \Delta$.

Suppose that the atom is initially prepared in $|e\rangle$ state, and the optical field is in coherent state. Then the interaction between atom and coherent optical field will lead to the following evolution:

$$|e\rangle|\alpha\rangle \xrightarrow{U(t)} (1/2)[(|\alpha\rangle + |\alpha e^{2i\lambda t}\rangle)|e\rangle - (|\alpha\rangle - |\alpha e^{2i\lambda t}\rangle)|g\rangle] \quad (2)$$

Similarly, if the atom is initially prepared in $|g\rangle$ state, the evolution takes a new form:

$$|g\rangle|\alpha\rangle \xrightarrow{U(t)} (1/2)[(|\alpha\rangle + |\alpha e^{2i\lambda t}\rangle)|g\rangle - (|\alpha\rangle - |\alpha e^{2i\lambda t}\rangle)|e\rangle] \quad (3)$$

If we select the atomic velocity to realize the interaction time $t = \pi/(2\lambda)$, then Eqs (2, 3) will become:

$$|e\rangle|\alpha\rangle \xrightarrow{U(t)} (1/2)[(|\alpha\rangle + |-\alpha\rangle)|e\rangle - (|\alpha\rangle - |-\alpha\rangle)|g\rangle] \quad (4a)$$

*Electronic address: mingyang@ahu.edu.cn

†Electronic address: zlcao@ahu.edu.cn

$$|g\rangle|\alpha\rangle \xrightarrow{U(t)} (1/2)[(|\alpha\rangle + |-\alpha\rangle)|g\rangle - (|\alpha\rangle - |-\alpha\rangle)|e\rangle] \quad (4b)$$

Let $|\alpha_+\rangle = (1/\sqrt{2})(|\alpha\rangle + |-\alpha\rangle)$, $|\alpha_-\rangle = (1/\sqrt{2})(|\alpha\rangle - |-\alpha\rangle)$, then we get

$$|e\rangle|\alpha\rangle \xrightarrow{\lambda t=\pi/2} (1/\sqrt{2})[|\alpha_+\rangle|e\rangle - |\alpha_-\rangle|g\rangle] \quad (5a)$$

$$|g\rangle|\alpha\rangle \xrightarrow{\lambda t=\pi/2} (1/\sqrt{2})[|\alpha_+\rangle|g\rangle - |\alpha_-\rangle|e\rangle] \quad (5b)$$

From the analysis of coherent state [18], we get that : $|u\rangle = 1/\sqrt{2(1+e^{-2|\alpha|^2})}(|\alpha\rangle + |-\alpha\rangle)$, $|v\rangle = 1/\sqrt{2(1-e^{-2|\alpha|^2})}(|\alpha\rangle - |-\alpha\rangle)$ are two orthogonal basis. Here we use $|\alpha_+\rangle$ and $|\alpha_-\rangle$ to replace $|u\rangle$ and $|v\rangle$. In fact, when $|\alpha| = 3$, the approximation is rather perfect. So the entangled states in Eqs (5a, 5b) are maximally entangled states between the atom and the coherent optical field.

Next, we will give the evolution of the system for different initial state:

$$|e\rangle|-\alpha\rangle \xrightarrow{\lambda t=\pi/2} (1/\sqrt{2})[|\alpha_+\rangle|e\rangle + |\alpha_-\rangle|g\rangle] \quad (6a)$$

$$|g\rangle|-\alpha\rangle \xrightarrow{\lambda t=\pi/2} (1/\sqrt{2})[|\alpha_+\rangle|g\rangle + |\alpha_-\rangle|e\rangle] \quad (6b)$$

From Eqs (5a, 5b, 6a, 6b), we can give the following operations:

$$|\alpha_+\rangle|e\rangle \longrightarrow |\alpha_+\rangle|e\rangle \quad (7a)$$

$$|\alpha_+\rangle|g\rangle \longrightarrow |\alpha_+\rangle|g\rangle \quad (7b)$$

$$|\alpha_-\rangle|e\rangle \longrightarrow -|\alpha_-\rangle|g\rangle \quad (7c)$$

$$|\alpha_-\rangle|g\rangle \longrightarrow -|\alpha_-\rangle|e\rangle \quad (7d)$$

which are C-NOT operations from optical field to atom, and the operations:

$$|-\rangle|\alpha\rangle \longrightarrow |-\rangle|\alpha\rangle \quad (8a)$$

$$|-\rangle|-\alpha\rangle \longrightarrow |-\rangle|-\alpha\rangle \quad (8b)$$

$$|+\rangle|\alpha\rangle \longrightarrow |+\rangle|-\alpha\rangle \quad (8c)$$

$$|+\rangle|-\alpha\rangle \longrightarrow |+\rangle|\alpha\rangle \quad (8d)$$

which are C-NOT operations from atom to optical field. Where $|+\rangle = (1/\sqrt{2})(|e\rangle + |g\rangle)$, $|-\rangle = (1/\sqrt{2})(|e\rangle - |g\rangle)$.

With the C-NOT gates being realized, we can realize the generation of entangled atomic states and entangled coherent states. In addition, we also can realize the purification of the mixed entangled atomic states and mixed entangled coherent states.

Firstly, we will consider the generation of maximally entangled atomic states. After the first atom $|e_1\rangle$ has interacted with the coherent optical field for $t_1 = \pi/(2\lambda)$, the evolution of the system can be described by Eq (5a). Then the second atom, initially prepared in $|e_2\rangle$ state, will be sent through the field area. If the interaction time is still $t_2 = \pi/(2\lambda)$, the total evolution reads:

$$\begin{aligned} |\alpha\rangle|e_1\rangle|e_2\rangle &\xrightarrow{\lambda t_1=\pi/2} (1/\sqrt{2})[|\alpha_+\rangle|e_1\rangle|e_2\rangle - |\alpha_-\rangle|g_1\rangle|e_2\rangle] \\ &\xrightarrow{\lambda t_2=\pi/2} (1/\sqrt{2})[|\alpha_+\rangle|e_1\rangle|e_2\rangle + |\alpha_-\rangle|g_1\rangle|g_2\rangle] \end{aligned} \quad (9)$$

That is to say, after interactions the state of total system becomes:

$$|\Psi_{total}\rangle \longrightarrow (1/\sqrt{2})[|\alpha\rangle|\Phi_{12}^+\rangle + |-\alpha\rangle|\Phi_{12}^-\rangle] \quad (10)$$

where $|\Phi_{12}^+\rangle = (1/\sqrt{2})[|e_1\rangle|e_2\rangle + |g_1\rangle|g_2\rangle]$, $|\Phi_{12}^-\rangle = (1/\sqrt{2})[|e_1\rangle|e_2\rangle - |g_1\rangle|g_2\rangle]$ are two Bell states for atoms 1 and 2.

Then we will detect the optical field. If the result is $|\alpha\rangle$, the two atoms will be left in Bell state $|\Phi_{12}^+\rangle$; If the result is $|-\alpha\rangle$, the two atoms will be left in Bell state $|\Phi_{12}^-\rangle$.

In fact, if we do not detect the optical field after the second atom flying out of the cavity, multi-atom entangled states can be created. We will send the next atom ($|e_n\rangle$) through the field area after the previous one flying out of it. Then after the last atom flying out of the cavity field, the optical field will be detected. Conditioned on different results, the n atoms will be left in different maximally entangled states:

$$\begin{aligned}
|\Psi_n\rangle \longrightarrow & (1/\sqrt{2})[(1/\sqrt{2})(|e_1\rangle|e_2\rangle \cdots |e_n\rangle + (-1)^n|g_1\rangle|g_2\rangle \cdots |g_n\rangle)|\alpha\rangle \\
& + (1/\sqrt{2})(|e_1\rangle|e_2\rangle \cdots |e_n\rangle + (-1)^{(n-1)}|g_1\rangle|g_2\rangle \cdots |g_n\rangle)|-\alpha\rangle]
\end{aligned} \tag{11}$$

Secondly, we will consider the generation of maximally entangled coherent states. Let an atom, initially prepared in $|e\rangle$ state, interact with the first coherent optical field. Let the interaction time satisfy $t_1 = \pi/(2\lambda)$. Af-

ter flying out of the first cavity, the atom will be sent through the second cavity field, and the interaction time is still $t_2 = \pi/(2\lambda)$. The evolution of the total system is:

$$|e\rangle|\alpha_1\rangle|\alpha_2\rangle \xrightarrow{\lambda t_1=\pi/2} (1/\sqrt{2})[(-)|\alpha_1\rangle + |+\rangle|-\alpha_1\rangle)|\alpha_2\rangle] \xrightarrow{\lambda t_2=\pi/2} (1/\sqrt{2})[(-)|\alpha_1\rangle|\alpha_2\rangle + |+\rangle|-\alpha_1\rangle|-\alpha_2\rangle] \tag{12}$$

which can be expressed in another form:

$$|\Psi_{total}\rangle \longrightarrow (1/\sqrt{2})[(1/\sqrt{2})(|\alpha_1\rangle|\alpha_2\rangle + |-\alpha_1\rangle|-\alpha_2\rangle)|e\rangle + (1/\sqrt{2})(|\alpha_1\rangle|\alpha_2\rangle - |-\alpha_1\rangle|-\alpha_2\rangle)|g\rangle] \tag{13}$$

If we measure the state of the atom in basis $|e\rangle, |g\rangle$, we can get the maximally entangled state of the two cavity fields: $(1/\sqrt{2})(|\alpha_1\rangle|\alpha_2\rangle + |-\alpha_1\rangle|-\alpha_2\rangle)$ for result $|e\rangle$, $(1/\sqrt{2})(|\alpha_1\rangle|\alpha_2\rangle - |-\alpha_1\rangle|-\alpha_2\rangle)$ for $|g\rangle$,

Like the generation of n -atom maximally entangled

state, after the atom flying out of the second cavity, we will not measure the atomic state. Instead, we will send it through other coherent optical fields one by one. In each cavity, the interaction time are all equal to $t = \pi/(2\lambda)$. Then we can get the n -cavity maximally entangled states:

$$\begin{aligned}
|\Psi_n\rangle \longrightarrow & (1/\sqrt{2})[(1/\sqrt{2})(|\alpha_1\rangle|\alpha_2\rangle \cdots |\alpha_n\rangle + |-\alpha_1\rangle|-\alpha_2\rangle \cdots |-\alpha_n\rangle)|e\rangle \\
& + (1/\sqrt{2})(|\alpha_1\rangle|\alpha_2\rangle \cdots |\alpha_n\rangle - |-\alpha_1\rangle|-\alpha_2\rangle \cdots |-\alpha_n\rangle)|g\rangle]
\end{aligned} \tag{14}$$

Due to cavity decay, the two-mode maximally entangled coherent state in Eq (13) more easily evolve into a mixed state. So next we will consider the purification of the mixed entangled coherent state [19, 20, 21].

Suppose we have generated two pairs of the two-mode entangled states of optical fields, and cavities 1, 3 are in the access of one user Alice, cavities 2, 4 are in the access of the other user Bob. At each side, there will be an auxiliary atom, denoted by a or b . With the help of the Ramsey Zones between the two cavities. We can realize the C-NOT operations from cavity 1 to cavity 3, and from cavity 2 to cavity 4.

Here atoms a, b are all prepared at $|e\rangle$ state, and the

Ramsey Zones all have the same function, i.e. it can realize the following rotations: $|e\rangle \rightarrow |+\rangle = (1/\sqrt{2})(|e\rangle + |g\rangle)$, $|g\rangle \rightarrow |-\rangle = (1/\sqrt{2})(|e\rangle - |g\rangle)$. Then consider the purification procedure. The auxiliary atom a will be sent through the cavity 1, Ramsey Zone R_a , and cavity 3 one after another. The interaction times between atom a and cavity 1, cavity 3 are all equal to $t = \pi/(2\lambda)$. Then we find that, if the state of cavity 1 is expressed in $\{|\alpha_+\rangle, |\alpha_-\rangle\}$ basis, and the state of cavity 3 is expressed in $\{|\alpha\rangle, |-\alpha\rangle\}$ basis, this interaction sequence will realize the C-NOT operations from cavity 1 to cavity 3:

$$|\alpha_+\rangle_1|e_a\rangle|\pm\alpha_3\rangle \xrightarrow{\lambda t_1=\pi/2} |\alpha_+\rangle_1|e_a\rangle|\pm\alpha_3\rangle \xrightarrow{R_a} |\alpha_+\rangle_1|+\rangle_a|\pm\alpha_3\rangle \xrightarrow{\lambda t_3=\pi/2} |\alpha_+\rangle_1|+\rangle_a|\mp\alpha_3\rangle \tag{15a}$$

$$|\alpha_-\rangle_1|e_a\rangle|\pm\alpha_3\rangle \xrightarrow{\lambda t_1=\pi/2} |\alpha_-\rangle_1|g_a\rangle|\pm\alpha_3\rangle \xrightarrow{R_a} |\alpha_+\rangle_1|-\alpha\rangle|\pm\alpha_3\rangle \xrightarrow{\lambda t_3=\pi/2} |\alpha_+\rangle_1|-\alpha\rangle|\pm\alpha_3\rangle \quad (15b)$$

The two mixed states to be purified are:

$$\rho_{12} = F|\Phi^+\rangle_{12}\langle\Phi^+| + (1-F)|\Psi^+\rangle_{12}\langle\Psi^+| \quad (16a)$$

$$\rho_{34} = F|\Phi^+\rangle_{34}\langle\Phi^+| + (1-F)|\Psi^+\rangle_{34}\langle\Psi^+| \quad (16b)$$

where Eq (16a) is expressed in basis $\{|\alpha_+\rangle_1|\alpha_+\rangle_2, |\alpha_+\rangle_1|\alpha_-\rangle_2, |\alpha_-\rangle_1|\alpha_+\rangle_2, |\alpha_-\rangle_1|\alpha_-\rangle_2\}$, and Eq (16b) is expressed in basis $\{|\alpha_3\rangle|\alpha_4\rangle, |\alpha_3\rangle|-\alpha_4\rangle, |-\alpha_3\rangle|\alpha_4\rangle, |-\alpha_3\rangle|-\alpha_4\rangle\}$. Here the fidelity of the mixed state relative to the initial maximally entangled state is $F = \langle\Phi^+|\rho|\Phi^+\rangle$.

After the procedure described in Eqs (15a, 15b), we can measure the atoms a, b . There will be four possible results, $|e_a\rangle|e_b\rangle, |g_a\rangle|g_b\rangle, |e_a\rangle|g_b\rangle$, and $|g_a\rangle|e_b\rangle$. These four results can be divided into two kinds, $|e_a\rangle|e_b\rangle, |g_a\rangle|g_b\rangle$ and $|e_a\rangle|g_b\rangle, |g_a\rangle|e_b\rangle$. Corresponding to each kind, we all can get the purified entangled coherent state of cavity 1, 2 conditioned on the measurement result on cavity 3, 4 in the $\{|\alpha_3\rangle|\alpha_4\rangle, |\alpha_3\rangle|-\alpha_4\rangle, |-\alpha_3\rangle|\alpha_4\rangle, |-\alpha_3\rangle|-\alpha_4\rangle\}$ basis.

For the first kind of result $|e_a\rangle|e_b\rangle, |g_a\rangle|g_b\rangle$, we can get the new state of cavity fields 1, 2 provided that cavity fields 3, 4 are all in the same coherent state.

$$\rho_{12new} = F_{new}|\Phi^+\rangle_{12}\langle\Phi^+| + (1-F_{new})|\Psi^+\rangle_{12}\langle\Psi^+| \quad (17a)$$

$$F_{new} = \frac{F^2}{F^2 + (1-F)^2}. \quad (17b)$$

For the second kind of result $|e_a\rangle|g_b\rangle, |g_a\rangle|e_b\rangle$ we can get that:

$$\rho'_{12new} = F'_{new}|\Phi^-\rangle_{12}\langle\Phi^-| + (1-F'_{new})|\Psi^-\rangle_{12}\langle\Psi^-| \quad (18a)$$

$$F'_{new} = F_{new}. \quad (18b)$$

From the result in Eqs (17a, 18a, 17b, 18b), we find that the mixed entangled state in Eq (16a) has been purified through the C-NOT operations from cavities 1, 2 to cavities 3, 4 plus the measurements on atoms and cavities. Consider the first result as example. When $F > \frac{1}{2}$, $F_{new} > F$. So the mixed state in Eq (16a) has been purified. Because the initial Fidelity F is an arbitrary number between 0.5 and 1.0, the iteration of the above scheme can extract a entangled coherent state with an degree of entanglement arbitrarily close to 1.0. The same analysis applies to the second result.

In the above scheme, the C-NOT operations from one cavity to another has been realized using the highly detuned interaction between three-level Λ -type atoms and coherent optical fields. In fact, using this kind of interaction we also can realize the C-NOT operations from one atom to another.

Let the first atom (1) through a cavity, initially prepared in coherent state. The interaction is governed by the Hamiltonian expressed in Eq (1). After the first atom flying out of the cavity, we can complete the rotational operation on the coherent state of the cavity: $|\alpha\rangle \rightarrow |\alpha_+\rangle, |-\alpha\rangle \rightarrow |\alpha_-\rangle$ by using nonlinear Kerr medium [22]. Then we will sent the second atom (2) through the cavity. If the interaction times between the cavity and atoms 1, 2 are all equal to $t = \pi/(2\lambda)$, the total evolution of the system can be expressed as:

$$|+\rangle_1|\alpha\rangle|e_2\rangle \xrightarrow{\lambda t_1=\pi/2} |+\rangle_1|-\alpha\rangle|e_2\rangle \xrightarrow{R} |+\rangle_1|\alpha_-\rangle|e_2\rangle \xrightarrow{\lambda t_2=\pi/2} |+\rangle_1|\alpha_-\rangle|g_2\rangle \quad (19a)$$

$$|+\rangle_1|\alpha\rangle|g_2\rangle \xrightarrow{\lambda t_1=\pi/2} |+\rangle_1|-\alpha\rangle|g_2\rangle \xrightarrow{R} |+\rangle_1|\alpha_-\rangle|g_2\rangle \xrightarrow{\lambda t_2=\pi/2} |+\rangle_1|\alpha_-\rangle|e_2\rangle \quad (19b)$$

$$|-\rangle_1|\alpha\rangle|e_2\rangle \xrightarrow{\lambda t_1=\pi/2} |-\rangle_1|\alpha\rangle|e_2\rangle \xrightarrow{R} |-\rangle_1|\alpha_+\rangle|e_2\rangle \xrightarrow{\lambda t_2=\pi/2} |-\rangle_1|\alpha_+\rangle|e_2\rangle \quad (19c)$$

$$|-\rangle_1|\alpha\rangle|g_2\rangle \xrightarrow{\lambda t_1=\pi/2} |-\rangle_1|\alpha\rangle|g_2\rangle \xrightarrow{R} |-\rangle_1|\alpha_+\rangle|g_2\rangle \xrightarrow{\lambda t_2=\pi/2} |-\rangle_1|\alpha_+\rangle|g_2\rangle \quad (19d)$$

That is to say, we also realize the atom-to-atom C-NOT operations.

Then, because we have realized the C-NOT operations: atom-to-atom, field-to-field, atom-to-field and field-to-atom, the teleportation schemes for unknown coherent superposition state of cavity and unknown atomic states can be easily realized [3]. That is to say, the joint Bell state measurement will be carried out by sending an atom through a detuned optical field, i.e. the Bell state measurement will be converted into the product single atom measurement and single field measurement.

The detection of coherent field has been realized by B.Yurke *et al* [22], and they can distinguish $|\alpha\rangle$ and $|\alpha\rangle$ by homodyne detection. So the detection of coherent field in our scheme is realizable, and the detection of atom can be realized by the field-induced ionization [23].

We now consider the implementation of the above-mentioned scheme. The atoms used in our scheme are all λ -type three level atoms with one excited level and two degenerate ground levels, which can be achieved by using Zeeman sublevels. From the discussion in [24], by using Rydberg atom of long lifetime and superconducting microwave cavities with an enough high-Q, there is sufficient time to achieve our schemes in experiment.

In conclusion, Using the highly detuned interaction between three-level λ -type atoms and coherent optical

fields, the C-NOT operations from atoms to atoms, optical fields to optical fields, from atoms to optical fields and from optical fields to atoms all have been realized in cavity QED. Our scheme not only can generate multi-atom entangled states but also can generate multi-mode entangled coherent states. Based on the C-NOT gates, the entanglement purification for mixed entangled coherent states and teleportation of unknown states of atoms or fields all have been proposed. In the previous quantum information processing proposals, many atoms are required to interact with single mode field simultaneously. In our scheme, only the interaction between single atom and single mode field is needed, which avoids the problem of the synchronization of many atoms in the previous quantum information processing proposals.

Acknowledgments

This work is supported by the Natural Science Foundation of the Education Department of Anhui Province under Grant No: 2004kj005zd and Anhui Provincial Natural Science Foundation under Grant No: 03042401 and the Talent Foundation of Anhui University.

-
- [1] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. 47, 777 (1935).
 - [2] J. S. Bell, Physics (Long Island City, N.Y.) 1, 195 (1965).
 - [3] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. 70, 1895 (1993).
 - [4] D. Bouwmeester, J-W. Pan, et al, Nature, 390, 575-579(1997).
 - [5] C. H. Bennett and S. J. Wiesner, Phys. Rev. Lett. 69, 2881(1992).
 - [6] K. Mattle, H. Weinfurter, P. G. Kwiat, & A. Zeilinger, Phys. Rev. Lett. 76, 4656-4659 (1996).
 - [7] A. Ekert, Phys. Rev. Lett. 67, 661 (1991).
 - [8] C. H. Bennett, G. Brassard, and N. D. Mermin. Phys. Rev. Lett. 68, 557(1992).
 - [9] D. Bouwmeester, J-W. Pan, M. Daniell, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. 82, 1345-1349 (1999).
 - [10] N. Gershenfeld and I. L. Chuang, Science 275, 350(1995).
 - [11] S. L. Braunstein, C. M. Caves, R. Jozsa, N. Linden, S. Popescu, and R. Schack, Phys.Rev.Lett. 83 1054-1057(1999).
 - [12] A. Lamas-Linares et. al. Nature 412, 887 (2001).
 - [13] A. Rauschenbeutel, G. Nogues, S. Osnaghi, P. Bertet, M. Brune, J.M. Raimond, and S. Haroche, Science 288, 2024 (2000).
 - [14] S-B. Zheng and G-C. Guo, Phys. Rev. Lett. 85, 2392 (2000).
 - [15] Q. A. Turchette, C. S. Wood, B. E. King, C. J. Myatt, D. Leibfried, W. M. Itano, C. Monroe, and D. J. Wineland, Phys. Rev. Lett. 81, 3631C3634 (1998)
 - [16] S. Osnaghi, P. Bertet, A. Auffeves, P. Maioli, M. Brune, J. M. Raimond, and S. Haroche, Phys. Rev. Lett. 87, 037902 (2001)
 - [17] L. Xu, Z. M. Zhang, Z. Phys. B 95, 507 (1994).
 - [18] S. J. van Enk, O. Hirota, Phys. Rev. A 64, 022313 (2001).
 - [19] C. H. Bennett, G. Brassard, S. Popescu, B. Schumacher, J. A. Smolin, & W. K. Wootters, Phys. Rev. Lett. 76, 722 (1996).
 - [20] J. W. Pan, S. Gasparoni, R. Ursin, G. Weihs & A. Zeilinger, Nature 423, 417 (2003).
 - [21] Ming Yang, Wei Song, Zhuo-Liang Cao, Phys. Rev. A 71, 012308 (2005).
 - [22] B. Yurke and D. Stoler, Phys. Rev. Lett. 57, 13(1986).
 - [23] J. M. Raimond, M. Brune, and S. Haroche, Reviews of Modern Physics, 73 565(2001).
 - [24] S. B. Zheng, Quant. Semiclass. Opt. B 10, 691 (1998); K.-H. Song, W.-J. Zang, and G.-C. Guo, Eur. Phys. J. D 19, 267(2002).